Tangent Length and Sight Distance Effects on Accident Rates at Horizontal Curves on Rural Two-Lane Highways

KENNETH L. FINK AND RAYMOND A. KRAMMES

Most models for evaluating operating-speed consistency on two-lane rural highways estimate operating-speed profiles based on tangent length and degree of horizontal curvature. Some models also consider the effect of sight distance to horizontal curves. To add insight on the effects of these variables on safety and operations at horizontal curves, a base relationship between accident rates at horizontal curves and degree of curvature was established, and the effects of approach tangent length and approach sight distance on this relationship were examined. The results confirm that degree of curvature is a good predictor of accident rates on horizontal curves. Although the effects of approach tangent length and sight distance were not as clear, the results suggest that the adverse safety effects of long approach tangent length and short approach sight distance become more pronounced on sharp curves.

Accident research has consistently found that accident rates on horizontal curves are 1.5 to 4 times the accident rates on tangent sections of rural two-lane highways (*1*). Most studies have found that the degree of curvature is the primary factor in the prediction of accidents on horizontal curves. (In the metric system of measurements, degree of curvature—the angle subtended by a 100-ft arc of curve—is replaced by radius as the measure of curve sharpness.)

Geometric design consistency principles suggest that, in addition to its degree of curvature, a curve's location relative to adjacent horizontal alignment features (i.e., tangent lengths) and vertical alignment features (i.e., sight distance to the curve) is an important factor in safe operations on curves. The standard procedure for evaluating geometric design consistency on rural two-lane highways is to develop a profile of 85th percentile speeds along the alignment and estimate the speed reductions required between successive horizontal alignment features (principally between approach tangents and curves). Whereas tangent length is a key variable in all procedures for evaluating operating-speed consistency, there are conflicting views on the role of sight distance. Some procedures assume sight distance to curves has no effect on operating-speed profiles, whereas other procedures account for sight distance.

Consistency evaluations require additional effort in the design process. In order to justify this additional effort, it would be necessary to demonstrate that it yields additional insight into the safety and operational effects of alternative alignment geometries. Krammes et al. (*2*) developed a speed-profile model for evaluating operating-speed consistency and conducted accident analysis to assess the benefits of speed reductions as a predictor of accident rates at horizontal curves on rural two-lane highways.

Alternative forms of the speed-profile model employed different assumptions about the effect of sight distance on speed profiles. One form assumed that sight distance has no effect on speed profiles; that is, the distance upstream of the curve at which any necessary deceleration begins is independent of the distance upstream at which the curve becomes visible, which may be a reasonable assumption for drivers familiar with the roadway. The alternative form assumed that the distance upstream of the curve at which any necessary deceleration begins cannot be greater than the distance upstream at which the curve becomes visible, which is a more reasonable assumption for unfamiliar drivers. These different assumptions affect speed reduction estimates only for a subset of curves at which drivers would accelerate to a higher speed on the approach tangent due to the limited available approach sight distance than if greater approach sight distance were available.

The accident analysis compared speed reduction estimates and degree of curvature as predictors of accident rates at horizontal curves. A sample of 1,126 curve sites was grouped into intervals of speed reduction or degree of curvature. The mean speed reduction or degree of curvature and mean accident rate for the curves in each interval were computed, and the mean speed reductions or mean degrees of curvature were regressed against the mean accident rates. For intervals of curve sites requiring no speed reduction (i.e., degree of curvature $\leq 4°$), mean accident rates did not differ significantly; whereas for intervals of curve sites requiring speed reduction (i.e., degree of curvature $> 4°$) mean accident rates increased approximately linearly with both mean degree of curvature and mean speed reduction. It was also concluded that considering the effect of sight distance to curves in the speed-profile model improved the prediction of mean accident rates. These results suggest that speed reduction estimates do provide additional insights into accident experience at horizontal curves and imply that tangent length and/or sight distance may explain some of the variability in accident rates left unexplained by degree of curvature alone.

This study describes follow-up research that was performed to examine more explicitly the effect of approach tangent length and sight distance on accident rates at horizontal curves on rural two-lane highways. First, design guidelines and accident research on tangent length and sight distance to horizontal curves are reviewed. Second, the analysis methodology is described. Next, the analysis results are presented. The final section provides a summary and conclusions.

BACKGROUND

Design Guidelines

The AASHTO (*3*) briefly addresses the issues of tangent length and sight distance relative to horizontal curve design in *A Policy on Geometric Design of Highways and Streets*. AASHTO provides the

K. L. Fink, Kimley-Horn and Associates, Inc., 3001 Weston Parkway, Cary, N.C. 27513. R. A. Krammes, Texas Transportation Institute, Texas A&M University, College Station, Tex. 77843.

guidance that "sharp horizontal curves should not be introduced at the end of long tangents" (*3*). Unfortunately, AASHTO does not define what constitutes a "sharp" curve and a "long" tangent. The guidance on vertical sight distance to horizontal curves is also limited: "sharp horizontal curves should not be introduced at or near the top of a pronounced crest vertical curve" (*3*). Again the designer is left to define "sharp," "near," and "pronounced."

Other countries that employ speed-consistency-based procedures are more precise. Germany, France, and Switzerland have guidelines on maximum lengths for tangents to avoid driver fatigue (*4*). In Germany, tangent lengths are limited by the design speed.

Sight distance criteria in the United States and Europe are similar. Most countries use a stopping sight distance model to determine the minimum allowable sight distance for a given speed along a roadway. U.S. criteria are relatively conservative. French guidelines also set a minimum value for sight distance to horizontal curves (measured from the driver's eye to the pavement surface at the beginning of the curve) as three seconds at the 85th percentile speed on the approach tangent (*5*). The Swiss have a similar guideline that sight distance to a curve should be greater than the required deceleration distance to the curve at 0.8 mpss (2.6 fpss) (*6*).

Literature Review

Four previous studies have considered tangent length among a set of candidate predictors of accident rates at horizontal curves (*7–10*). Their findings with respect to tangent length were mixed. Datta et al. (*7*) found tangent length to be a significant predictor of outside-lane accident rates for one subset of their 25 curve sites in Michigan. Terhune and Parker (*8*) evaluated tangent length (among other variables) using data bases of 78 curves in New York, 40 curves in Ohio, and 41 curves in Alabama, and concluded that tangent length was not significant. Matthews and Barnes (*9*) studied 4,666 curves on the rural two-lane portion of a State highway in New Zealand; they found a significant relationship that involved tangent length in combination with other variables and concluded that accident risk was particularly high on short radius curves at the end of long tangents, on steep down grades, and on relatively straight sections of roads. Zegeer et al. (*10*) evaluated the significance of the minimum and maximum distance to the adjacent curve; although neither variable was significant, they observed, "there appears to be evidence that tangents above a certain length may result in some increase in accidents on the curve ahead." Although these studies are far from conclusive, they suggest a possible effect of tangent length that warrants further examination.

Four studies that examined the safety effects of sight distance on rural two-lane highways were relevant (*11–14*). Although only the study by Glennon et al. (*11*) focused on horizontal curves, the other studies' analyses of accident experience versus sight distance are pertinent to this study. Two of the four studies found a relationship between sight distance and accident rates. Both Olson et al. (*12*) and Paniati and Council (*14*) concluded that the available sight distance has a significant effect on accident rates. Paniati and Council (*14*) used a surrogate measure (the distance from the crest of a vertical curve to the accident) to represent sight distance, so the results cannot be taken literally as an effect of sight distance. Glennon et al. (*11*) concluded that approach sight distance was not a significant variable in a discriminant analysis of curve sites with high and low accident rates. Fambro et al. (*13*) concluded that available stopping sight distance is not a good indicator of accidents, with the exception that "when there are intersections within limited sight distance portions of crest vertical curves, there is a marked increase in accidents." The question about the effect of sight distance on accident rates at horizontal curves remains unanswered.

ANALYSIS METHODOLOGY

The primary objectives of the analysis were to evaluate whether there are statistically significant relationships between the following:

- Accident rates on horizontal curves and the approach tangent length; and
- Accident rates on horizontal curves and the sight distance to the curve.

The analysis was performed on the same database as the Krammes et al. (*2*) study. A base regression model of accident rate as a function of degree of curvature was established. Then, analyses were conducted to determine whether tangent length and sight distance were statistically significant when added to the base model.

Hypotheses

Driver expectancy and design consistency concepts suggest general relationships among degree of curvature, tangent length, sight distance, and accident rates at horizontal curves. These effects were stated as hypotheses that guided the analysis.

It is hypothesized that, at a given degree of curvature, accident rates are higher than average for curves with short approach tangents where drivers do not have enough time to recover from the previous feature, accident rates decrease for moderate approach tangent lengths, and they increase again when the tangent length becomes so long that the horizontal curve is unexpected and the driver is not mentally prepared for it. The effect of tangent length is hypothesized to increase as the degree of curvature at the end of the tangent increases.

It is further hypothesized that, for a given degree of curvature, accident rates decrease as sight distance to the curve increases. As sight distance decreases the driver has less time to react and prepare for the horizontal curve, thus creating a greater opportunity for accidents. This effect is expected to be more pronounced for higher degrees of curvature.

Database

The database contained geometry and accident data for a sample of curve sites selected from roadways in three States: New York, Washington, and Texas. Table 1 summarizes the site selection controls and criteria.

The database included 563 curves. Because approach tangent length and sight distance to the curve vary by direction, each curve lane (direction) was treated as a separate site. Thus, the final database consisted of curve geometry and accident data for 1,126 curve sites. Pertinent geometric and identifying information for each direction of each curve was obtained from both roadway plans and field measurements. Sight distance was measured as the distance upstream from the beginning of the curve at which the curve became visible to the driver.

Police accident reports for the roadway segments were studied in

TABLE 1 Site Selection Controls and Criteria

Control	Criteria
Area Type	Rural
Administrative Classification	State
Functional Classification	Collector or Arterial
Design Classification	Two-Lane
Design Speed	≤ 88.5 km/h (55 mph)
Posted Speed Limit	≤ 88.5 km/h (55 mph)
Terrain	Level to Rolling
Grade	≤ 5 percent
Pavement	High Type
Traffic Volumes	400-3500 vpd
Lane Widths	3.05-3.66 m (10-12 ft)
Shoulder Widths	0-2.44 m (0-8 ft)
Plan-Profile Sheets	Available
Accident Data	Available
RRR Improvements	None within past 5 years
Length of Route	≥ 4.0 km (2.5 miles)
Distance from a Town	≥ 0.8 km (0.5 miles)
Distance from End of Roadway	≥ 0.8 km (0.5 miles)
Intersections	None within Curve Site

order to obtain detailed descriptions of each accident and to verify the type and location of accidents. Five years of accident data (1987 through 1991) were included for the curve sites in Washington and Texas. In New York, however, the police accident reports had been destroyed through October 1988; therefore, only 3 years and 2 months of accident data were included for sites in New York. The accident reports were analyzed to eliminate accidents that were clearly unrelated to the geometry of the roadway (e.g., animal in road, driver asleep) and to include only accidents within the curve proper (i.e., between the point of curvature and point of tangency). Furthermore, due to the limited number of accidents involving large trucks and motorcycles, they were also excluded from the analysis. Thus, the database contained 235 reported accidents involving passenger vehicles at horizontal curves. The accidents included all severity levels: property-damage-only (129 accidents), and injury/fatality (106 accidents). Accident types included run off the road (213 accidents) and both same-direction and opposite-direction multiple vehicle collisions (22 accidents)—types identified by Zegeer et al. (*10*) as being "overrepresented on curves when compared to tangents."

Statistical Analysis

Regression analysis was performed with accident rate as the dependent variable. The independent variables were degree of curvature, approach tangent length, and sight distance to the curve. Previous analysis of this database considered several additional independent variables (state, deflection angle, travel-way width, and total pavement width) and concluded that they were not statistically significant predictors of accident rates (*2*).

Because degree of curvature has proven to be a good predictor of accidents, the first step in the analysis was to establish a regression model between accident rate and degree of curvature that would serve as the basis for the analysis of tangent length and sight distance. Due to the limited size of the database, sites were grouped into nine categories of degree of curvature. The mean degree of curvature in each category was computed. The mean accident rate per million vehicle kilometers of travel at the curve sites in each category was computed by dividing the total number of reported accidents (including all accident types and severity levels) at the curve sites in the category by the sum of the vehicle kilometers traveled at those curve sites during the time period covered by the accident data. Table 2 summarizes the characteristics of the curve sites in each category.

The base regression model had the following form:

$$\text{Mean accident rate} = \beta_0 + \beta_1 \text{ mean degree of curvature}$$

The natural logarithm of the mean accident rate was also considered as the form of the dependent variable.

The effects of tangent length and sight distance were evaluated separately. Within each degree of curvature category, the curve sites were further grouped into tangent length or sight distance categories. Indicator (0–1) variables were added to the base regression model so that different intercepts and slopes could be estimated for each tangent length or sight distance category. Differences between the slopes and intercepts of the relationships between mean accident rate and mean degree of curvature for different tangent length or sight distance categories were tested for statistical significance. Figures 1 and 2 illustrate the hypothesized differences.

The significance level for all statistical tests was at $\alpha = 0.05$. Analyses were performed using the Statistical Analysis System (SAS) (*15*).

RESULTS

Mean Accident Rate Versus Mean Degree of Curvature

The regression model for mean accident rate per million vehicle kilometers versus mean degree of curvature was as follows:

$$\text{Mean accident rate} = 0.05 + 0.23 \text{ mean degree of curvature.}$$

Figure 3 is a plot of the regression model. The model has an r^2 value of 0.94. The root mean square error was 0.33 accidents per million vehicle kilometers. The model was statistically significant at $\alpha = 0.05$. These results suggest a strong and approximately linear relationship. The r^2 value is much higher than typically observed in accident analyses, because the unit of observation is a grouping of curve sites into degree-of-curvature categories which eliminates much of the variability among individual sites.

Relationship Between Accident Rate and Approach Tangent Length

Several stratifications of tangent length were tested. For example, one stratification used the three cases of tangent length based on

TABLE 2 Curve Site Characteristics by Degree-of-Curvature Category

Category	# of Curve Sites	# of Accidents	Range of D (°)	Mean D (°)	Mean Tangent Length (m)	Mean Sight Distance (m)
1	112	10	≤1	0.9	455	211
2	154	14	1-≤2	1.9	380	184
3	136	22	2-≤3	2.9	420	174
4	160	20	3-≤4	3.8	321	180
5	84	19	4-≤5	4.9	354	161
6	128	27	5-≤6	5.8	343	208
7	106	40	6-≤8	7.5	291	177
8	120	44	8-≤11	9.8	248	135
9	126	39	>11	18.3	314	170

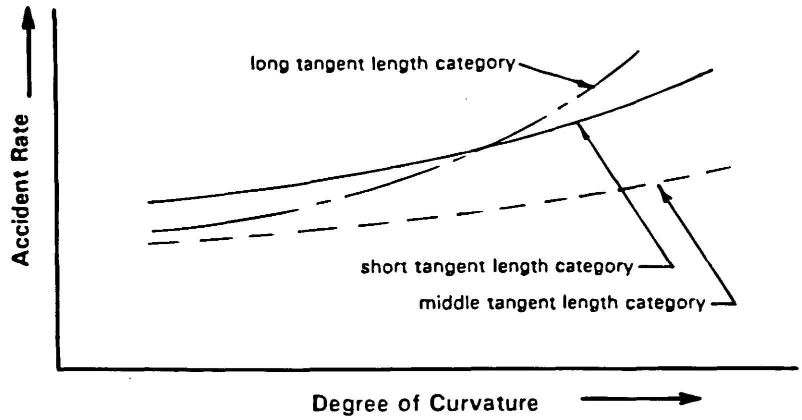

FIGURE 1 Hypothesized relationship between curve accident rate and degree of curvature category for three tangent length categories.

acceleration-deceleration patterns between successive curves in the speed-profile model; unfortunately, the paucity of data in the shortest tangent length category made the regression results unreliable.

In order to ensure a reasonable number of curve sites representing short, moderate, and long tangent lengths, three categories were defined representing the shortest 25 percent [≤107 m (350 ft)], middle 50 percent [107 m (350 ft) to 427 m (1400 ft)], and longest 25 percent [>427 m (1400 ft)] of tangent lengths in the database. The regression models were as follows:

- Shortest 25%: mean accident rate = 0.35 + 0.16 mean degree of curvature;
- Middle 50%: mean accident rate = −0.30 + 0.32 mean degree of curvature;
- Longest 25%: mean accident rate = 0.52 + 0.20 mean degree of curvature.

Figure 4 illustrates the relationships. The results indicate that the slope and intercept for the middle 50 percent of tangent lengths are significantly different from the slope and intercept for the longest 25 percent (at $\alpha = 0.05$). Although there are some statistically significant effects, the lack of consistently strong patterns in Figure 4 tempers the strength of conclusions that can be drawn. Two general findings seem warranted. First, the results support the hypothesis that the effect of longer approach tangents becomes more pronounced at higher degrees of curvature. Second, the results do not support the hypothesis that short tangent lengths increase safety problems.

Relationship Between Accident Rate and Sight Distance to a Curve

The process of selecting sight distance categories was similar to the one for establishing the tangent length categories. Several stratifications of sight distance were considered.

One stratification was based on the French sight distance criterion (i.e., a distance equivalent to 3 s at the 85th percentile approach speed). The database was broken into two categories of sight distance values: less than or equal to the French sight distance criterion, and greater than the criterion. The results with this analysis yielded no significant differences between the categories.

Another stratification was based on the deceleration distance on the approach tangent upstream of the curve calculated by the speed-profile model (*2*). The database was divided into categories of sight distances less than or equal to the required deceleration distances and sight distances greater than the required deceleration distance.

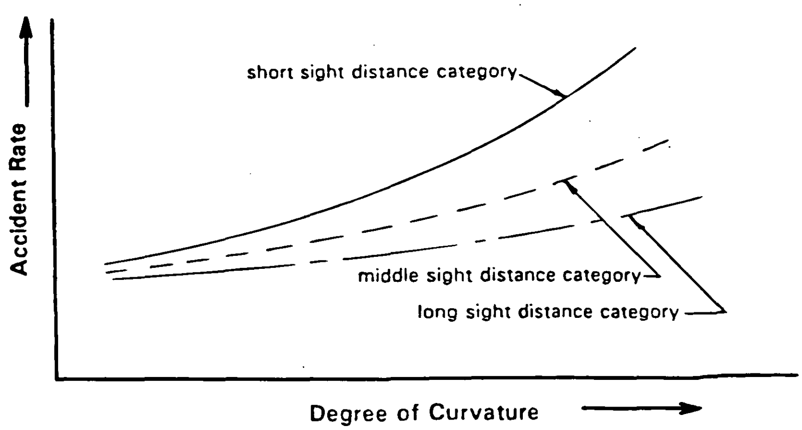

FIGURE 2 Hypothesized relationship between curve accident rate and degree of curvature category for three sight distance categories.

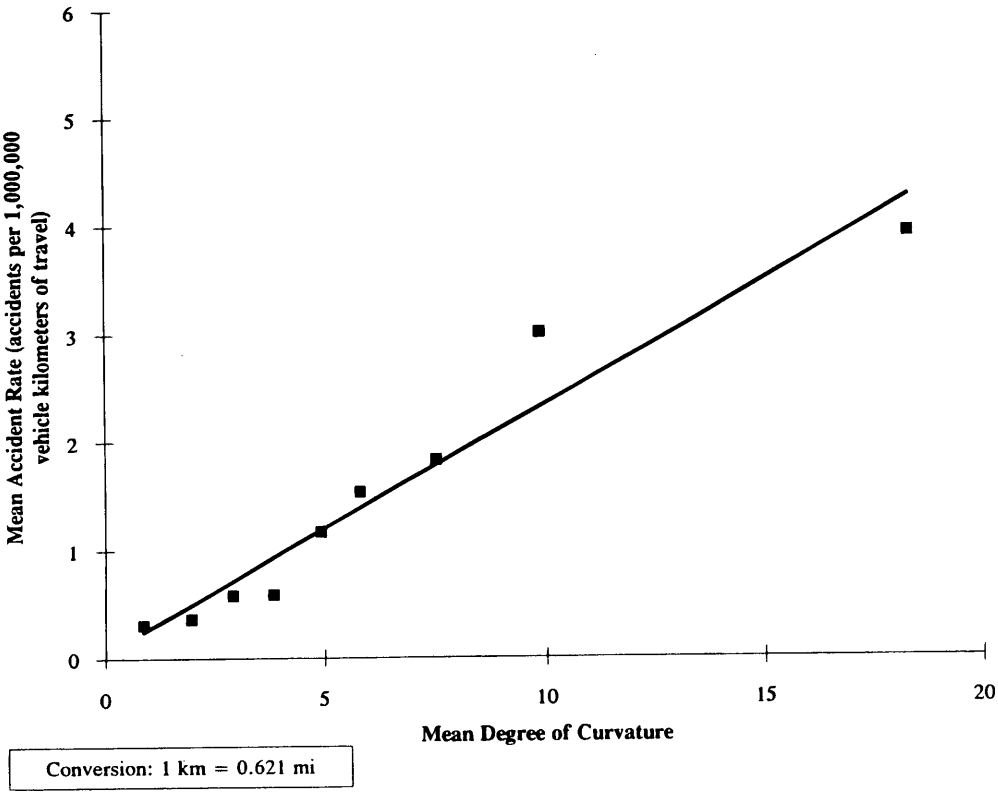

FIGURE 3 Mean accident rate versus mean degree of curvature.

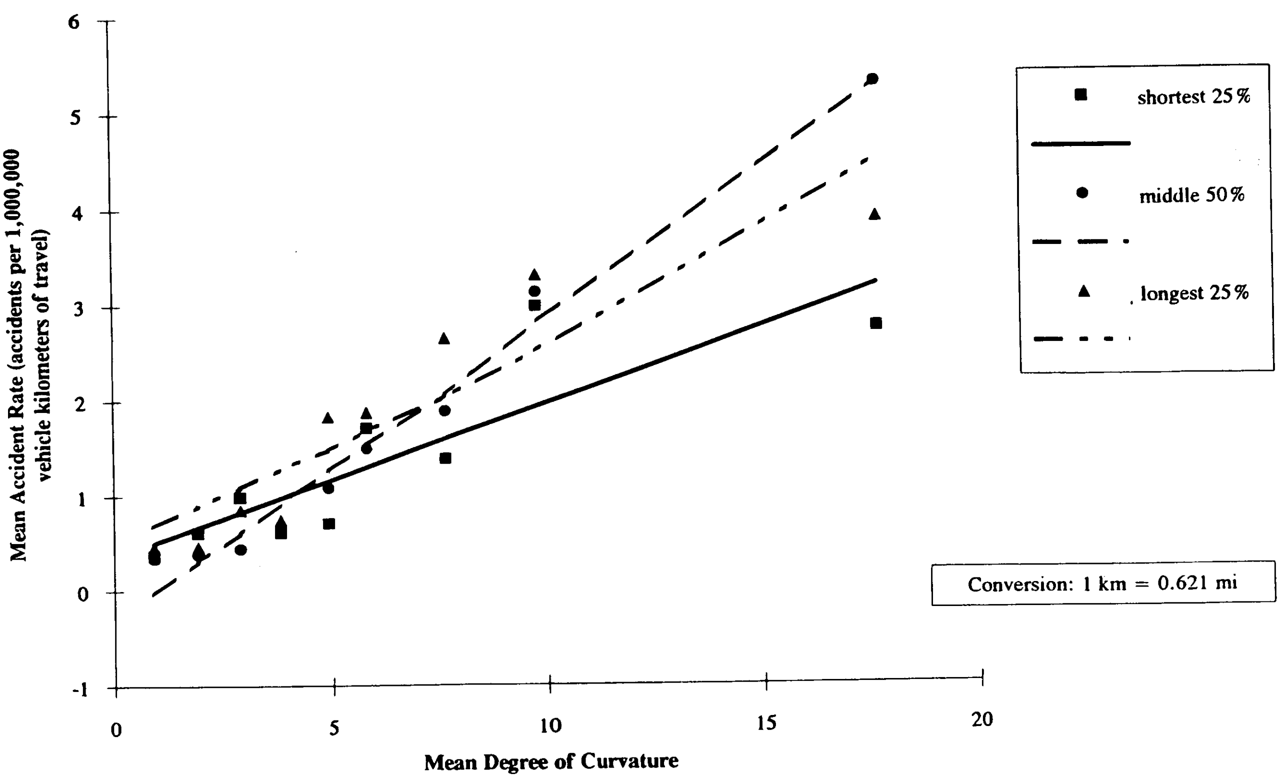

FIGURE 4 Mean accident rate versus tangent length category.

Because only 6 percent of the curve sites had approach sight distance less than the required deceleration distance, the analysis with these categories was not considered reliable.

The results presented in this study are based on categories representing the shortest 25th percent [≤61 m (200 ft)], middle 50th percent [61 m (200 ft) to 213.5 m (700 ft)], and longest 25 percent [>213.5 m (700 ft)] of sight distances in the database. With respect to stopping sight distance guidelines, the shortest sight distance category corresponds to design speeds less than 50 km/h (approximately 30 mi/h), the middle to design speeds between 50–100 km/h (approximately 30–60 mi/h), and the longest to design speeds greater than 100 km/h (approximately 60 mi/h).

The regression models for these three categories are:

- Shortest 25%: mean accident rate = −0.29 + 0.30 mean degree of curvature;
- Middle 50%: mean accident rate = 0.52 + 0.16 mean degree of curvature;
- Longest 25%: mean accident rate = −0.12 + 0.29 mean degree of curvature.

Figure 5 illustrates the relationships. Although the intercepts of the three equations do not differ significantly, the slopes for the shortest and longest sight-distance categories are significantly different from the slope for the middle sight-distance category (at $\alpha = 0.05$). As with the tangent length results, the scatter in Figure 5 tempers the conclusions that can be drawn. The steeper slope for the shortest sight distance category compared to the middle sight distance category is as hypothesized and suggests that the adverse safety effects of short approach sight distance—corresponding to design speeds less than 50 km/h (approximately 30 mi/h)—become more pronounced as the sharpness of curve increases. Contrary to the hypothesized relationships, however, the slope for the longest sight distance category is also steeper than the middle sight distance category. This result may be explained by the likelihood that most sites with long approach sight distance also have long approach tangent lengths. The greater speed reductions associated with long tangents may outweigh the benefits of long sight distance.

CONCLUSIONS

The results in this study are consistent with previous research: the relationship between accident rates and degree of curvature is clear and easy to quantify, whereas the effect of other factors is less clear and more difficult to quantify. A strong relationship between accident rate and degree of curvature category was developed.

The effects of approach tangent length and sight distance are not as clear. The results suggest that the effect of long tangent lengths becomes more pronounced on sharper curves, which is consistent with conventional wisdom and previous research and supports the benefits of evaluating speed consistency. The analysis of sight distance effects also suggests that extreme approach conditions (both long and short approach sight distance) may contribute to higher accident rates on sharper curves. Additional research to more clearly define critical ranges of approach tangent lengths and sight distance seem warranted.

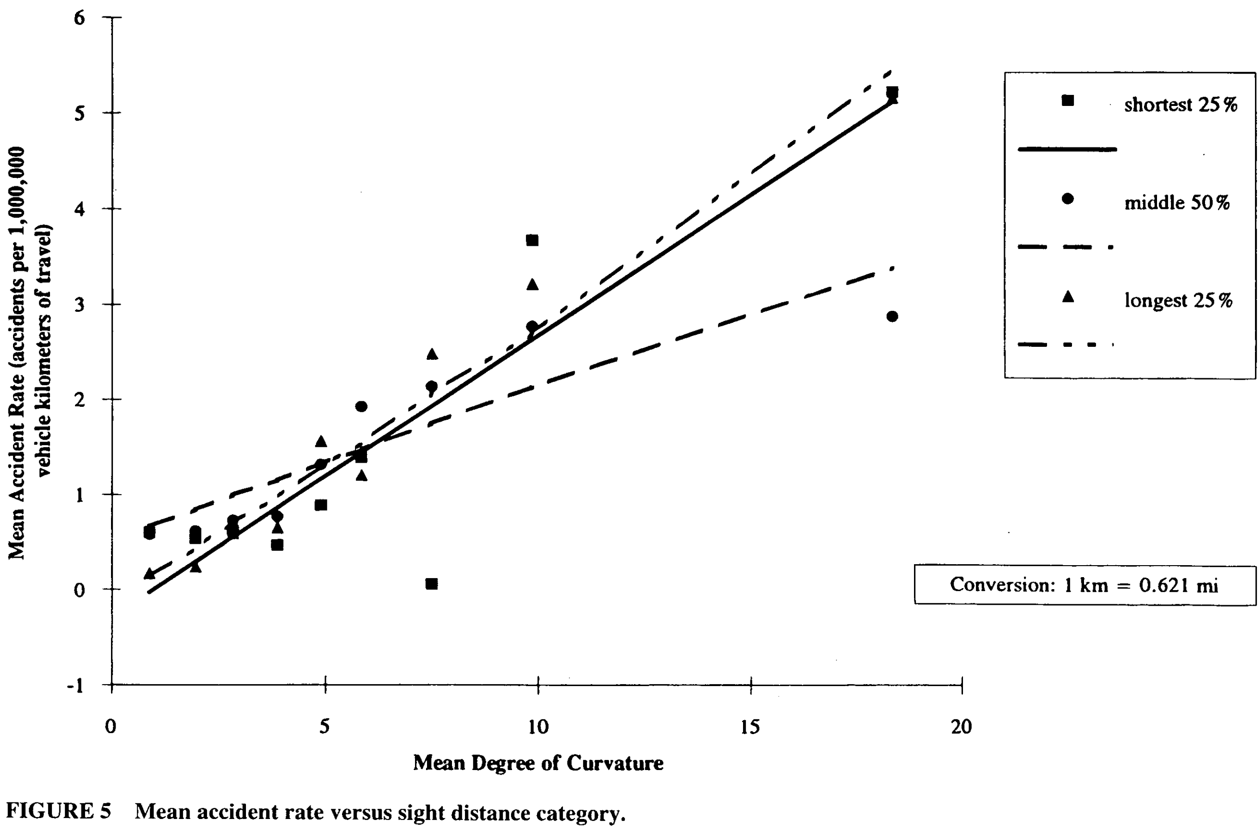

FIGURE 5 Mean accident rate versus sight distance category.

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